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Droop-Controlled DC Microgrids: Mesh and Radial Configurations for Improved Load Power Sharing

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Abstract:

Fair power distribution requires taking into account the capabilities of the converters installed at each interface. In order to make sure that all converters are working under ideal circumstances and that the radial and mesh designs are considered, this paper suggests a new method for enhancing the precision of load power sharing in DC microgrids that are controlled by droop. Two terms are used for compensation: average DC voltage management of nearby converters and average output power control. If the data from the neighboring converter is used just, the communication network may be made simpler. In order to distribute load power reasonably in conditions of variable line resistance, modified droop control—which may be seen as a distributed method—is used. Through low bandwidth communication, sampled data is sent across converters. An extensive investigation is conducted into various network topologies and line resistances under varied communication delays to ascertain the practicability and effectiveness of the suggested approach. The proposed approach is supported by the outcomes of a MATLAB/Simulink model of a three-converter DC microgrid. The testing results of a 3x10kW prototype further show that the proposed revised droop control method is effective.

Keywords: Interruptions in communication, handling of drops, sharing of power under loads, radial and mesh designs, and direct current microgrids

Introduction

These days, a lot of people are talking about how to use and create renewable energy sources [1,2]. The use of microgrids to handle several renewable energy sources simultaneously is becoming more common [3]. Distributed power systems, or microgrids, typically employ alternating current (AC). However, DC output is provided by the fuel cell, energy storage devices, photovoltaic (PV) systems, and other similar technologies. That being said, DC-type microgrids might prove to be more practical when it comes to improving power quality and increasing efficiency. It is vital that the power be distributed equitably and effectively since transmission lines carry it from generators to customers [4, 5]. Power electronic converters are also essential in DG because of renewable energy legislation requirements. By avoiding the need of specialized communication between converters, an improved droop control method was presented in [10] to reduce line loss and increase the efficiency of DC power systems in general. Using this method simultaneously has the potential to increase the accuracy of load distribution while simultaneously decreasing the voltage loss. Another drawback of heavy communication traffic is the need to sample data from all converters. Meanwhile, radial layout is our exclusive area of interest. A more sophisticated droop control method is suggested in this study to fix these problems. Regulating factors are selected based on the average voltage and output power of nearby converters. To keep the communication burden minimal, we merely use the information from nearby converters. A relatively low data transmission rate is used to transmit the voltage and power data from each converter via a network. The method delves into the effects of line impedance and the accuracy of power sharing. It is possible that the method's stability will be enhanced due to the absence of a central controller in the control system. Both radial and mesh system designs are studied. Results from both simulated and experimentally-based case studies demonstrate the viability and efficacy of the proposed approach. The outline of the paper is provided in this part. In Section 2, we discuss the issues with traditional methods of droop control. Issues with droop control are further examined in Section 3. Improved droop control is discussed in Section 4. Next, Section 5 compares and contrasts the results from the experiments with those from the simulations.

Conventional Methods of Sagging Control Current Developments in Direct Current Microgrids

DC microgrids have been the subject of much research in recent years because to the rising prevalence of distributed sources with DC output such photovoltaic (PV), battery storage, and the fuel cell. The following examples highlight their benefits, which extend to technical areas of control as well as cost-effective operation and efficiency:

DC microgrids have easier modelling and control since there is no phase angle, frequency, or reactive power; AC systems have more complex control systems because of the need to account for synchronization, reactive power flow, and harmonics. Moreover, DC is favored over AC because it is compatible with the vast majority of today's electronic loads, energy storage devices, and DG technologies. The total cost of ownership, infrastructure, equipment, maintenance, and operation are all lower in DC microgrids, and the existing literature highlights this fact. • Economical operation [13-15]: Economical operation in DC microgrids can be achieved without complex and computation-intensive optimization algorithms. Effectiveness (16-18): As inverter conversion losses between DC output sources and loads are decreased, overall system efficiency improves. Due to the DC capacitor's stored energy and the AC/DC converter's voltage management, DC microgrids have an inherent fault-ride-through capacity.

Consideration of Controlling Drooping

The following analysis examines the aforementioned problems with the conventional droop control approach, paying special attention to the mesh and radial layouts.

Mesh Layout

The converter output current for mesh and radial configurations in DC microgrids may be computed by utilizing the stated voltage and current equations based on the numerous nodes of the simplified system models. The Kirchhoff's law-derived circuit equations are shown in Figure 2a below.

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$$\begin{cases} v_{L} = R_{L} \cdot i_{L} \\ i_{L} = i_{dc1} + \dfrac{v_{dc2} - v_{dc1}}{r_{1L}} + i_{dc3} + \dfrac{v_{dc2} - v_{dc3}}{r_{3L}} \end{cases}$$

$$\begin{cases} i_{dc1} = \dfrac{v_{dc1} - v_{L}}{r_{1L}} - \dfrac{v_{dc2} - v_{dc1}}{r_{12}} \\ i_{dc2} = \dfrac{v_{dc2} - v_{dc1}}{r_{12}} + \dfrac{v_{dc2} - v_{dc3}}{r_{23}} \\ i_{dc3} = \dfrac{v_{dc3} - v_{L}}{r_{3L}} - \dfrac{v_{dc2} - v_{dc3}}{r_{23}} \end{cases}$$

where vdci is DC side output voltage of converter # i (i = 1, 2, 3), idci is DC side output current, vL is load voltage, iL is load side current, RL is load side resistance, rij (i = 1, 2, 3, j = 2, 3) is line resistance between different converters; Ri is the virtual resistance. Based on above circuit analysis and combining Equations (2) and (3), DC side output current can be obtained:

$$\begin{cases} i_{dc1} = \dfrac{1}{\lambda}\begin{pmatrix} [-(R_3 + 2R_L + r_{3L})r_{23}^2 - (R_2R_3 + 2R_2R_L + 2R_3R_L - R_2r_{3L} - R_3r_{2L})r_{23} - 2R_2R_3R_L]r_{12}^2 v_{dc}^* \\ -[R_2r_{23}^2(R_3 + r_{3L}) + 2R_2R_Lr_{23}(R_3 + r_{23}) + R_2R_3r_{23}(r_{3L} + r_{1L})]r_{12}v_{dc}^* \end{pmatrix} \\ i_{dc2} = \dfrac{1}{\lambda}\begin{pmatrix} (-R_1R_3r_{23} - 2R_3R_Lr_{23} - R_3r_{23}r_{1L})r_{12}^2 v_{dc}^* \\ -[R_1R_3r_{23}(r_{23} + r_{3L} + r_{1L}) + R_3r_{23}^2(2R_L + r_{1L}) + 4R_1R_3R_Lr_{23}]r_{12}v_{dc}^* \end{pmatrix} \\ i_{dc3} = \dfrac{1}{\lambda}\begin{pmatrix} [-(R_1 + r_{1L})r_{23}^2 - (R_1R_2 + 2R_2R_L + R_2r_{1L})r_{23}]r_{12}^2 v_{dc}^* \\ -[(2R_L + r_{1L})(R_1 + R_2)r_{23}^2 + R_1R_2r_{23}(r_{3L} + r_{23} + r_{1L} + 2R_L)]r_{12}v_{dc}^* - 2R_1R_2R_Lr_{23}^2v_{dc}^* \end{pmatrix} \end{cases}$$

Where

$$\lambda = \begin{pmatrix} 2R_2R_3R_L^2 - (r_{1L}r_{3L} + R_1R_3 + R_1R_L + R_3r_{3L} + R_3R_L + R_3r_{1L} + R_Lr_{1L} + R_Lr_{3L})r_{23}^2 - \\ [(r_{1L}r_{3L} + 2R_Lr_{3L})(R_2 + R_3) + (R_3 + R_L)R_1R_2 + (R_1 + R_2)R_3R_L + (R_2R_3 + R_2R_L + R_3R_L)r_{1L}]r_{23} \end{pmatrix} r_{12}^2$$
$$- \begin{pmatrix} [(R_3 + R_L)R_1R_2 + (R_1 + R_2)(R_3R_L + R_3r_{1L} + R_Lr_{3L} + R_Lr_{1L} + r_{1L}r_{3L}) + R_1R_2r_{3L}]r_{23}^2 - \\ [2R_2R_L^2(R_3 + R_1) - [(R_1 + R_2)R_3R_L + (R_3 + R_L)R_1R_2](r_{1L} + r_{3L}) - R_3r_{1L}r_{3L}(R_1 + R_2) - R_2R_3r_{1L}r_{3L}]r_{23} \\ -2R_1R_2R_3R_L(2R_L + r_{1L}) \end{pmatrix} r_{12}$$
$$+ 2R_3R_2R_Lr_{23}(R_1r_{23} + 2R_1R_L + R_1r_{3L})$$

In DC microgrids, by using traditional droop control method, accurate load power sharing accuracy can be obtained when the converter DC output power is set to be inversely proportional to the corresponding droop coefficient, the following expression can be obtained:

$$\frac{m_0}{k_1}\underbrace{[i_{dc1}(v_{dc}^* - \frac{m_0}{k_1}i_{dc1}v_{dc1})]}_{P_{dc1}} = \frac{m_0}{k_2}\underbrace{[i_{dc2}(v_{dc}^* - \frac{m_0}{k_2}i_{dc2}v_{dc2})]}_{P_{dc2}} = \frac{m_0}{k_3}\underbrace{[i_{dc3}(v_{dc}^* - \frac{m_0}{k_3}i_{dc3}v_{dc3})]}_{P_{dc3}}$$

Based on the above analysis, it can be seen that the power sharing error can be eliminated if and only if the droop coefficient and line impedance satisfy the relationship in Equation (5). However, this assumption is only suitable for an ideal system and the practical system is not satisfied. This is the limitation of the traditional droop control method in the mesh configuration of DC microgrids.

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Proposed Approach In order to solve

the two problems of induced traditional droop control, this paper proposes a method of controlling the average values of the DC-link voltage of adjacent converters as well as the output power to compensate the voltage deviation induced by droop control, and simultaneously improve the load power sharing accuracy. The whole control diagram of the system is given in Figure 4. Compared to the existing method of averaging the voltage and power based on global information, the improved control method alleviates the communication traffic and further reduces the dependence on the communication system. The DC-link voltage references of the two adjacent converters are as follows:

$$v_{dci}^{*} = v_{dc}^{*} - \frac{m_0}{k_i} P_{dci} \cdot G_{LPF} + \underbrace{\left(v_{dc}^{*} - \frac{G_d \cdot v_{dc(i-1)} + G_d \cdot v_{dc(i+1)}}{2}\right) \cdot G_{piv}}_{\text{Compensating Controller I}} - \underbrace{\left(P_{dci}/k_i - \frac{G_d \cdot P_{dc(i-1)} + G_d \cdot P_{dc(i+1)}}{2}\right) \cdot G_{pip}}_{\text{Compensating Controller II}}$$

where پ݀□ ∗ is output DC-link voltage reference of the ith converter, پ݀∗ is line DC-link voltage reference,

$$v_{dc(i-1)} \text{ and } v_{dc(i+1)}$$

are the output voltages of the ith converter's two adjacent converters, ۀ݀□ is the ith converter's output power?ۀ

$$P_{dc(i-1)} \text{and } P_{dc(i+1)}$$

are the output power of the itch converter's two adjacent converters, ki is the proportional sharing accuracy of output power, m0 is the coefficient of traditional droop control, GLPF is low pass filter introduced in droop control, ωs is the cut-off frequency of the filter, Gpiv and Gpip are two compensating terms of improved droop control: The averaging voltage controller and averaging power controller, are both traditional PI controllers. The communication delay of the transfer variable is Gd, which can be expressed as the following

$$G_{pip} = k_{pp} + \frac{k_{ip}}{s}$$

$$G_{piv} = k_{pv} + \frac{k_{iv}}{s}$$

$$G_d = \frac{1}{1+\tau s}$$

in the control system, low bandwidth communication is employed to transfer the sampling data of the DC-link voltage and power values between different converter units. Voltage deviations induced by droop control can be eliminated by PI controllers I for the average values of DC-link voltage and power respectively. However, there is a variety of renewable energy distributed into microgrids by multiple converters, which are separate and have no need of high frequency telecommunication lines. Hence, the sampling for all the transmission voltage and power between the converters will cause unnecessary errors

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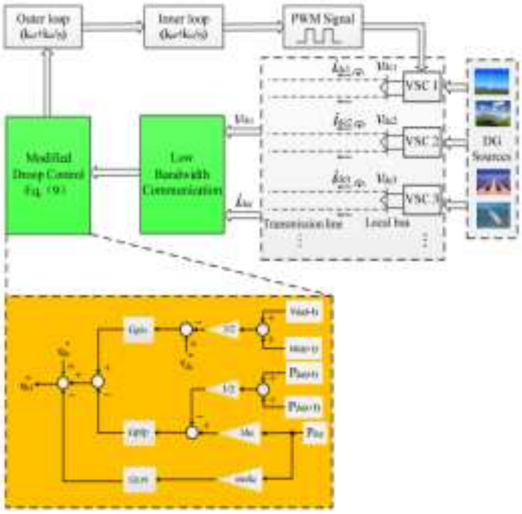

Figure 4. Detailed diagram of the proposed droop control system.

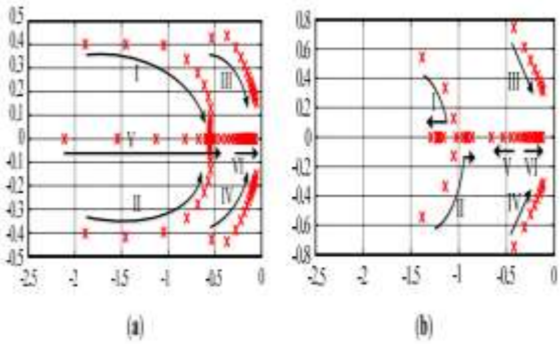

Figure 5. Closed-loop dominant poles for varying communication delay. (a) Mesh configuration (b) Radial configuration.

When communication delays are changed from 1 second to 10 seconds, as shown in Figure 5b, the position of the dominating closed-loop poles in the radial design shifts. The stability of the system is not compromised since poles I, II, and V remain on the left side of the s plane. However, if communication latency and loss increase, poles III, IV, and VI shift toward an imaginary axis, leading to an unstable state.

Compilations with Real-World Data

The performance of the suggested approach of better droop control was simulated using MATLAB/Simulink, and the viability of the control method was confirmed by taking into account varied line resistance rij, and communication latency, based on two distinct configurations. Table 1 displays the DC microgrids system's parameters. When comparing converters, the DC side power and DC side voltage are defined as follows, with maximum and lowest values shown in parentheses.

$$\varepsilon_j = \max(P_{dci}) - \min(P_{dci})$$

$$\varepsilon_j \leq 0.1 \times P_{dci}$$

$$\delta_j = \max(v_{dci}) - \min(v_{dci})$$

$$\delta_j \leq 0.05 \times v_{dci}$$

where i = 1, 2, 3 denotes the converter's sequence number, j = 1, 2, 3, 4 denotes the type of specific case.

Table 1. DC microgrids system parameters

Item	Symbol	Value
Reference of DC output voltage	v_{dc}	380 V
Load resistance	R_L	19 Ω
Power sharing proportion (Converter #i=1,2,3)	k_i	1
LPF cutting frequency	f_c	20 Hz
Communication delay	τ	0.1 s or 1 s
Droop coefficient	m_0	0.0015
Averaging voltage controller proportion coefficient	k_{pv}	2×10^{-1}
Averaging voltage controller integral coefficient	k_{iv}	4.5×10^{-2}
Averaging power controller proportion coefficient	k_{pp}	2.3×10^{-3}
Averaging power controller integral coefficient	k_{ip}	5.5×10^{3}

Mesh configuration						Radial configuration				
Case No.	r_{1L}	r_{12}	r_{23}	r_{3L}	τ	Case No.	r_{1L}	r_{2L}	r_{3L}	τ
1	0.8 Ω	1.0 Ω	1.0 Ω	1.2 Ω	0.1 s	4	0.8 Ω	1.0 Ω	1.2 Ω	0.1 s
2	0.8 Ω	1.0 Ω	1.0 Ω	1.2 Ω	1 s	5	0.8 Ω	1.0 Ω	1.2 Ω	1 s
3	0.6 Ω	1.2 Ω	1.2 Ω	1.8 Ω	1 s	6	0.6 Ω	1.2 Ω	1.8 Ω	1 s

Conclusions

A modified distributed control approach for mesh and radial layout was presented and investigated to enhance the overall performance of a droop-controlled DC microgrid. This paper's main arguments are summed up as follows: (1) Both mesh and radial topologies were shown to be capable of ensuring the feasibility and stability of the control system. (2) The updated droop control approach may reduce local DC output voltage variation and improve the accuracy of load power sharing. Third, the suggested control approach only uses voltage and current data sampled from two neighbouring converters, making the communication system less taxed. (4) The control system is reliable, even with a bigger mismatch in line resistance and a longer communication delay time.

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